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Sensitivity analysis of seismic hazard for the northwestern portion of the state of Gujarat, India

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Abstract

We test the sensitivity of seismic hazard to three fault source models for the northwestern portion of Gujarat, India. The models incorporate different characteristic earthquake magnitudes on three faults with individual recurrence intervals of either 800 or 1600 years. These recurrence intervals imply that large earthquakes occur on one of these faults every 266–533 years, similar to the rate of historic large earthquakes in this region during the past two centuries and for earthquakes in intraplate environments like the New Madrid region in the central United States. If one assumes a recurrence interval of 800 years for large earthquakes on each of three local faults, the peak ground accelerations (PGA; horizontal) and 1-Hz spectral acceleration ground motions (5% damping) are greater than 1 *g* over a broad region for a 2% probability of exceedance in 50 years' hazard level. These probabilistic PGAs at this hazard level are similar to median deterministic ground motions. The PGAs for 10% in 50 years' hazard level are considerably lower, generally ranging between 0.2 *g* and 0.7 *g* across northwestern Gujarat. Ground motions calculated from our models that consider fault interevent times of 800 years are considerably higher than other published models even though they imply similar recurrence intervals. These higher ground motions are mainly caused by the application of intraplate attenuation relations, which account for less severe attenuation of seismic waves when compared to the crustal interplate relations used in these previous studies. For sites in Bhuj and Ahmedabad, magnitude (M) 7 3/4 earthquakes contribute most to the PGA and the 0.2- and 1-s spectral acceleration ground motion maps at the two considered hazard levels.

Keywords: Seismic hazard; Magnitude; Gujarat, India

1. Introduction

The state of Gujarat has experienced several damaging earthquakes during the past two centuries (Fig. 1). Most of these events ruptured faults in the western portion of the state near the Pakistan border, known as the Kachchh region. In 1819, an earthquake

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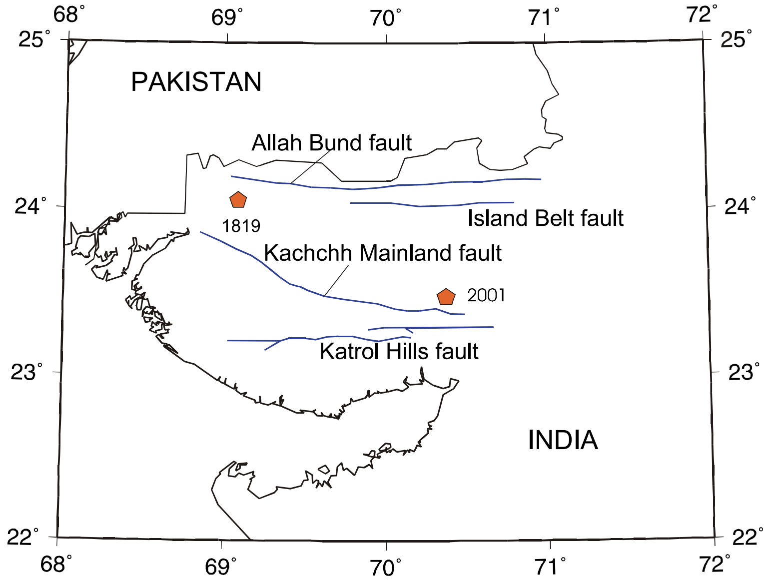

Fig. 1. Faults considered in hazard analysis along with the location of the 1819 Allah Bund and 2001 Bhuj earthquakes.

[magnitude (M) 7.8] ruptured the Allah Bund Fault in northwestern Gujarat, causing widespread collapse of structures and between 1500 and 2000 fatalities near the cities of Bhuj and Anjar (Bendick et al., 2001; Malik et al., 2000). A M 6.1 earthquake occurred near the Katrol Hill fault in 1956 and also caused damage in Anjar (Malik et al., 2000). On January 26, 2001, the Bhuj earthquake (M 7.7) occurred near the Kachchh Mainland fault (USGS location 23.419°N, 70.233°E, 17 km depth) and caused widespread damage, again affecting the cities of Bhuj and Anjar. The Bhuj earthquake was one of the most destructive earthquakes in Indian history, causing over 20,000 deaths and 166,000 injuries, and damaging or destroying over a million structures while leaving 600,000 people homeless (Directorate of Information, Government of Gujarat, 2001). The region has also experienced several damaging moderate-sized earthquakes with magnitudes between 5 and 6 (Fig. 1; Bendick et al., 2001). Nine of these moderate earthquakes occurred during the past 155 years in the region, an average of about one event every 17 years. Large and moderate earthquakes are likely to continue in the future and it is essential to assess the hazard to aid engineers and public officials in making informed planning decisions that will influence the economic and life safety policies for Gujarat. This paper is a summary of our findings pertaining to the ground motion hazard of the region, stemming from a request by the Chief Minister of Gujarat to provide some preliminary hazard assessments for assistance in making postearthquake rebuilding decisions.

Previous seismic hazard assessments have been conducted by the Bureau of Indian Standards (Krishina, 1992) and the Global Seismic Hazard Assessment Program (GSHAP; Zhang et al., 1999; Bhatia et al., 1999). Several early versions of the national seismic hazard maps were produced by the Bureau of Indian Standards in 1935, 1965, 1966, and 1970 (Krishina, 1992). Recently, the GSHAP program developed a regional source model for India, and peak ground acceleration (PGA) hazard was calculated for 10% probability of exceedance in 50 years on rock site conditions. The ground motions estimated by Bhatia et al. (1999) for GSHAP were assessed using the crustal interplate ground motion prediction equations of Boore et al. (1997), an updated seismicity catalog that incorporated several local catalogs and 86 seismic source zones. The seismic source zone used to account for seismicity in western Gujarat incorporates a maximum magnitude of 8.5, an annual rate of 0.126 M ≥5 earthquakes, and a Gutenberg–Richter *b* value of 0.55. The ground motion resulting from the

Bhatia et al. (1999) model for 10% probability of exceedance in 50 years has a maximum value of about 0.25 *g* for western Gujarat. The Bhatia et al. model was the basis for the India portion of the Zhang et al. (1999) GSHAP model, which assessed hazard for the entire continent of Asia. For the Kachchh region, Zhang et al. applied a modified maximum magnitude of 8.3, a background source zone that included earthquakes in eastern Pakistan, and ground motion prediction relations of Huo and Hu (1992) that were developed using strong motion data from China and the western United States. PGAs that were calculated for this region reach about 0.3 *g* for the 10% probability of exceedance in 50 years' hazard level.

The seismic sources in Gujarat are very uncertain and primary geological evidence on earthquake recurrence is based on geologic studies of the Allah Bund fault. Recurrence intervals of regional large earthquakes are very poorly constrained. In this paper, we test the sensitivity of the hazard to different magnitudes and recurrence rates. This hazard analysis includes updated sources (magnitudes), incorporates two crustal intraplate ground motion prediction relations (not interplate as in some previous analyses), and applies hazard methodologies that were used to produce the US National Seismic Hazard Maps (Frankel et al., 1996). The probabilistic hazard is calculated for the two hazard levels used in producing current US building codes: 2% and 10% probability of exceedance in 50 years. The deterministic hazard is calculated using the median ground motion from published ground motion prediction equations. We construct maps for PGA (horizontal) and 0.2 and 1.0 s spectral acceleration with 5% damping.

2. Source model

Many of the faults that have been identified in Gujarat are reactivated Mesozoic rift structures that are characterized by anticlinal folds at the surface (Rajendran and Rajendran, 2001; Wesnousky et al., 2001). The three faults considered in this seismic hazard analysis are the Allah Bund, Kachchh Mainland, and Katrol Hill faults (Fig. 1). Parameters used in the three source models are outlined in Table 1. Each of the three faults is located near moderate or large earthquakes that have occurred during the past 200 years and have produced strong ground motion in western Gujarat.

Malik et al. (1999) indicate that these and related faults have ruptured in numerous M 3 to 7 3/4 earthquakes during the past two centuries. Currently, it is not thought that the 1956 or 2001 events were located on any of the three structures included in our model; they were probably located on subparallel faults, other nearby faults, or blind structures that do not rupture up to the surface. The 2001 earthquake ruptured near the Kachchh Mainland fault, but no primary surface rupture has been identified in the field (Wesnousky et al., 2001; Rastogi, 2001). However, the aftershocks suggest that the rupture occurred on an unmapped, southward-dipping fault that would surface just north of the Kachchh Mainland fault (Rastogi et al., 2001; Bodin and Horton, 2004). The 1819 earthquake, on the other hand, caused up to 4.3 m of monoclinal folding along a 90-km trace of the mapped Allah Bund fault (Rajendran and Rajendran, 2001). Surface deformations produced by the earthquake indicate a north-dipping reverse fault (Rajendran and Rajendran, 2001). Rajendran and Rajendran (2001) suggest that the ages

Table 1
Seismic sources

Fault	Dip	Rupture top (km)	Rupture bottom (km)	Characteristic magnitude	Recurrence of characteristic magnitude
Allah Bund	North, 45°	1	20	M 7.8 (occurred in 1819; M 7.8 used in models 1–3)	800 years (models 1 and 2) and 1600 years (model 3)
Kachchh Mainland	South, 45°	1	40	M 7.7 (occurred in 2001; M 7.7 used in models 1–3)	800 years (models 1 and 2) and 1600 years (model 3)
Katrol Hill	Vertical	1	15	M 6.1 (occurred in 1956; used in model 1, or M 7.7 used in models 2 and 3)	800 years (models 1 and 2) and 1600 years (model 3)

of liquefaction features near the Allah Bund fault imply 800- to 1000-year recurrence intervals for earthquakes similar to the 1819 earthquake.

For this preliminary analysis, we have characterized large earthquakes on the three faults that have ruptured in moderate to large earthquakes, and recognize that these may be proxies for nearby structures. Faults characterized in this hazard analysis are part of a much larger, more complex fold and thrust belt. It is clear that future earthquakes will also occur on related structures that are not considered in this hazard assessment. For example, in this analysis, we did not include the 25-km-long Banni fault that is mapped just north of the Kachchh Mainland fault. Rupture of this fault would produce an earthquake much smaller than the other characterized faults, and we have no geologic information to estimate earthquake recurrence. Other faults have been mapped, but may not be active and capable of generating earthquakes. We did not include the Island Belt fault in this analysis because recent geologic studies indicate that the fault is not active (EERI Report, 2002).

Recurrence intervals for large earthquakes on faults included in our model are very poorly constrained. Therefore, we used a range of recurrence intervals to test the sensitivity of the hazard. We have applied the lower recurrence interval that was reported for the Allah Bund fault, about 800 years, as the lower limit of earthquake recurrence rates on each of the faults. We have also considered a recurrence interval that is a factor of 2 higher for the upper limit, which is 1600 years. Therefore, the rate of large earthquakes in the region (on any of these three faults) would range between 266 and 533 years, and the Poisson probability of having one or more of these earthquakes in the region in any 50-year period is between 9% and 17%.

The only historical interval for large earthquakes in the region is between the 1819 and 2001 earthquakes, or 182 years. In the New Madrid region of the central United States, liquefaction studies for intraplate events indicate a recurrence of about 500 years for large earthquakes (Tuttle et al., 2002). The range of recurrence that we have considered is consistent with the historical rate of earthquakes from one interval in western Gujarat and the recurrence rate of large earthquakes in an analogous intraplate environment. However, both of these recurrence estimates have large uncertainty and their applicability to northwestern Gujarat has not been justified.

3. Ground motion prediction equations

Gujarat is located within the India tectonic plate, about 500 km from a transform plate boundary (Bendick et al., 2001). There has been some recent debate about whether the Kachchh region should be considered as an interplate or intraplate tectonic regime (Lettis and Hengesh, 2001; Johnston, 2001; Schweig et al., 2003). The GSHAP models assumed the crustal interplate ground motion prediction equations of Boore et al. (1997) and Huo and Hu (1992). We compared ground motion data from the 2001 earthquake for sites located about 230 km from the hypocenter in Ahmedabad and 950 km from the hypocenter in Dehli (University of Rorkee; Cramer and Wheeler, 2001) that recorded the 2001 Bhuj earthquake with published ground motion attenuation equations. This comparison is to determine which attenuation relations are most applicable to the Kachchh region. The 2001 strong motion observations were on soil sites, and Cramer and Wheeler (2001) have calculated the response on typical rock sites. The median ground motions from the updated Sadigh et al. (1997) crustal interplate equations and the Frankel et al. (1996) crustal intraplate equation are shown in Fig. 2. It is important to keep in mind that the Sadigh et al. (1997) equations were primarily based on strong motion recordings at distances less than about 100 km, and that ground motion predictions at greater distances are extrapolations beyond the range suggested by the authors.

This comparison suggests that the crustal intraplate relation of Frankel et al. (1996) yields ground motions similar to the strong ground motion data recorded from the 2001 earthquake at large distances (Cramer and Wheeler, 2001). These intraplate ground motions are thought to be higher than ground motions predicted by interplate relations due to higher stress drops and lower attenuation properties. However, near-field ground motions in these intraplate relations are constrained mostly by theoretical models. Therefore, in our current model, we have calculated the hazard using the crustal

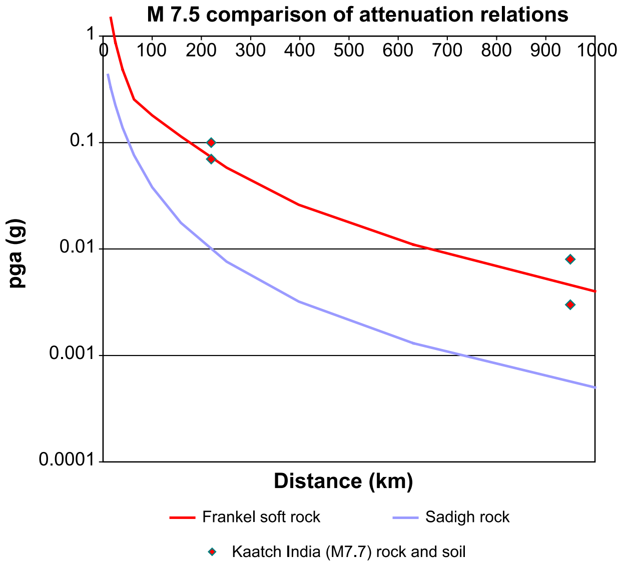

Fig. 2. Comparison of the different crustal interplate (Sadigh et al., 1997) and crustal intraplate (Frankel et al., 1996) ground motion prediction equations for M 7.5 with two data points from the 2001 Bhuj earthquake (M 7.7). Note that the upper symbol represents the PGA recorded on a soil site and the lower symbol represents the PGA calculated for a rock site by Cramer and Wheeler (2001).

intraplate ground motion prediction equations that were used to calculate the hazard in the 1996 US National Seismic Hazard Maps but have not emphasized the high ground motions calculated in the near-field region around the faults. The Toro et al. (1997) intraplate relation is similar but slightly lower than the relation produced by Frankel et al. (1996). We consider both intraplate attenuation relations to account for modeling (epistemic) uncertainty. The ground motions resulting from these intraplate models are significantly higher than ground motions calculated using the crustal interplate ground motion attenuation equations and, therefore, the ground motions in this analysis are higher than those calculated by GSHAP in 1999.

4. Probabilistic hazard model

We developed three probabilistic hazard models for the region of Gujarat by applying the methodologies used to produce the US National Seismic Hazard Maps (Frankel et al., 1996). The source model considers dipping faults that generate earthquakes with recurrence rates determined by paleoseismology and historic seismicity rates (Table 1). Data constraining recurrence intervals have been studied only for the Allah Bund Fault discussed earlier. We have calculated the hazard for three models:

1. Model 1: 800-year recurrence for each of the three faults with M 7.8 (Allah Bund), M 7.7 Kachchh Mainland, and M 6.1 (Katrol Hill); interevent time of M $\geq$7.7 earthquakes is about 400 years,
2. Model 2: 800-year recurrence for each of the three faults with M 7.8 (Allah Bund), M 7.7 Kachchh Mainland, and M 7.7 (Katrol Hill); interevent time of M $\geq$7.7 earthquakes is about 267 years,
3. Model 3: 1600-year recurrence for each of the three faults with the same magnitudes as applied in model 2; interevent time of M$\geq$7.7 earthquakes is about 533 years.

Model 1 considers the historic magnitudes of earthquakes that have occurred near these faults. Models 2 and 3 assume that the Katrol Hills fault could accommodate a larger earthquake than has been observed, about the size of the 2001 Bhuj rupture. We have considered this larger rupture because the Wells and Coppersmith (1994) relation indicates that the Katrol Hills could accommodate about a M 7 3/4 earthquake. Model 3 assumes that the recurrence intervals are twice as long as those we assumed in models 1 and 2.

5. Results: probabilistic models

We have calculated hazard curves for a grid of points across western Gujarat (Fig. 3). These hazard curves have a shallow slope and, therefore, the ground motions calculated for 2% probability of exceedance in 50 years (annual probability of 0.0004) are significantly higher than the 10% probability of exceedance in 50-year maps (annual probability of 0.0021).

Maps showing the 2% probability of exceedance in 50 years of ground motions indicate a high hazard over the entire region of northwestern Gujarat (Figs. 3–5). The hazard exceeds 1 *g* for PGA and 1-Hz spectral accelerations over a broad region. The highest hazard is located around the three sources considered in all three models. The near-fault ground motions are prominently displayed in maps with a 2% probability of exceedance in 50 years that have a return period of about 2500 years because this level is much longer than the 800-year recurrence of large earthquakes on individual faults. The ground motions are greater than 1 *g* for the 800- and 1600-year models at this 2% in 50 years' hazard level.

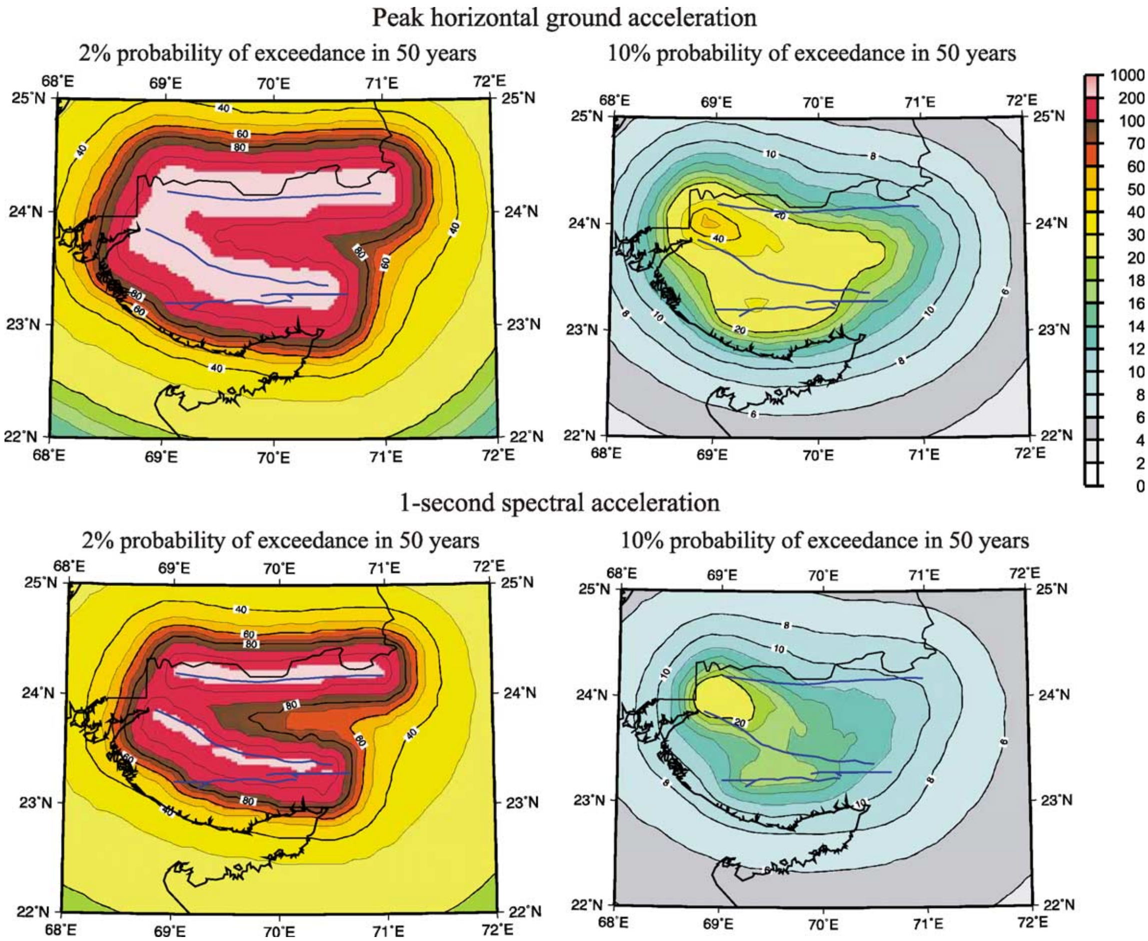

Fig. 3. Seismic hazard maps for western Gujarat for 2% and 10% probability of exceedance in 50 years based on model 1.

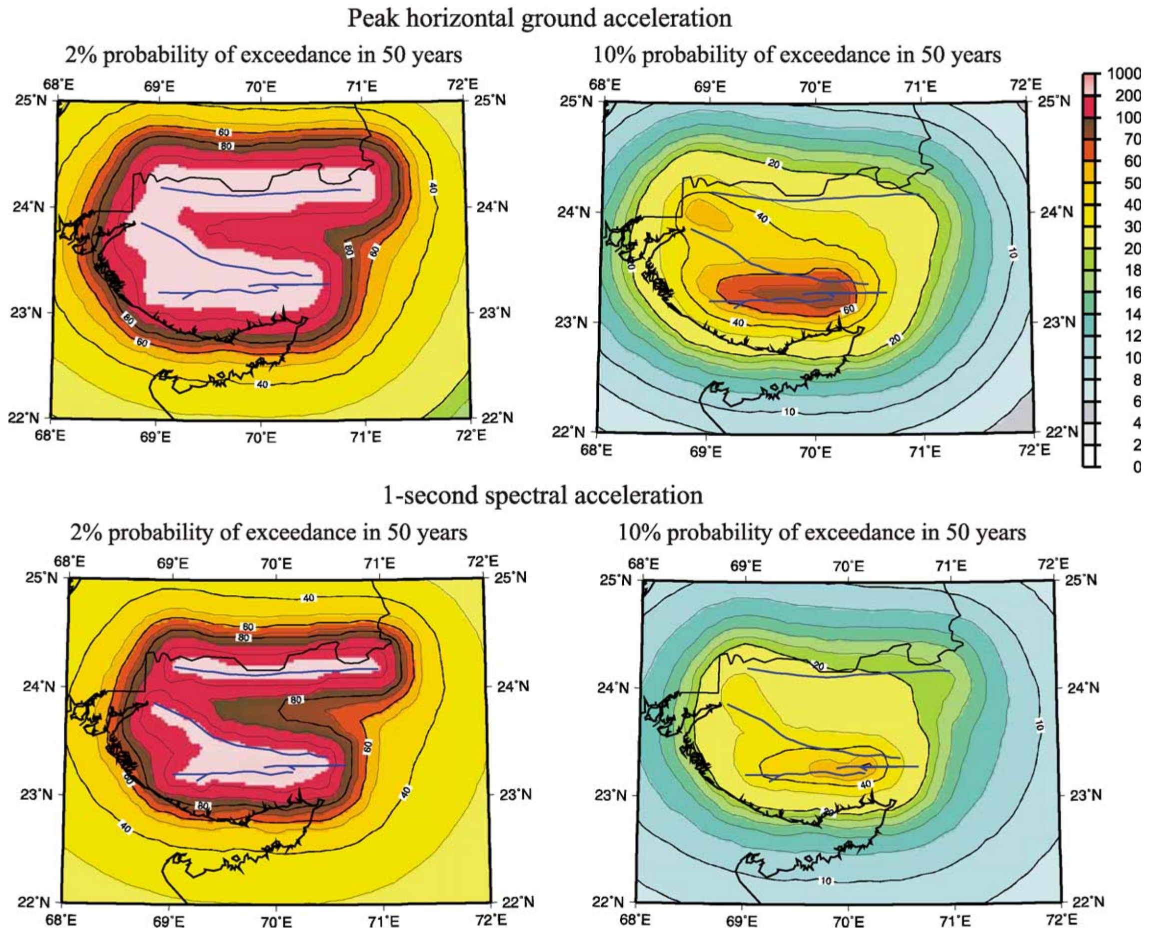

Fig. 4. Seismic hazard maps for western Gujarat for 2% and 10% probability of exceedance in 50 years based on model 2.

Maps showing the ground motions for 10% probability of exceedance in 50 years, on the other hand, are considerably lower than those for 2% in 50 years (Figs. 3–5). Nevertheless, the hazard is significant for structural design. PGAs reach 0.2–0.7 *g* for the 10% probability of exceedance in 50-year hazard maps. Spectral accelerations at 1 Hz (5% damping) exceed 0.15 *g* over a broad area at this hazard level. The 10% probability of exceedance in 50-year hazard maps indicates that ground motions are highest between the faults due to the influence of two or more fault sources. For example, the highest ground motions do not outline the Allah Bund fault because it occurs only every 800 years and the 10% probability of exceedance in 50-year maps has about a 500-year return period. Therefore, the maps do not reflect the high near-fault ground motions at this 500-year return period. Instead, the combined hazard from two 800-year sources on the Allah Bund and Kachchh Mainland faults cause the hazard to be elevated at sites between those structures, on average, every 400 years. Therefore, high hazard at the 10% probability of exceedance in 50-year hazard level is centered between the two faults. The geometry of the fault also is important in determining where the hazard is highest. For example, the recurrence of earthquakes on the Katrol Hill Fault, which is modeled as a vertical structure, and Kachchh Mainland fault, which dips to the south, causes a combined hazard that is highest over the Katrol Hills fault. At sites near the Katrol Hills fault, high ground motions are not only caused by earthquakes on the Katrol Hill fault, but also from earthquakes on the deeper portion of the Kachchh Mainland

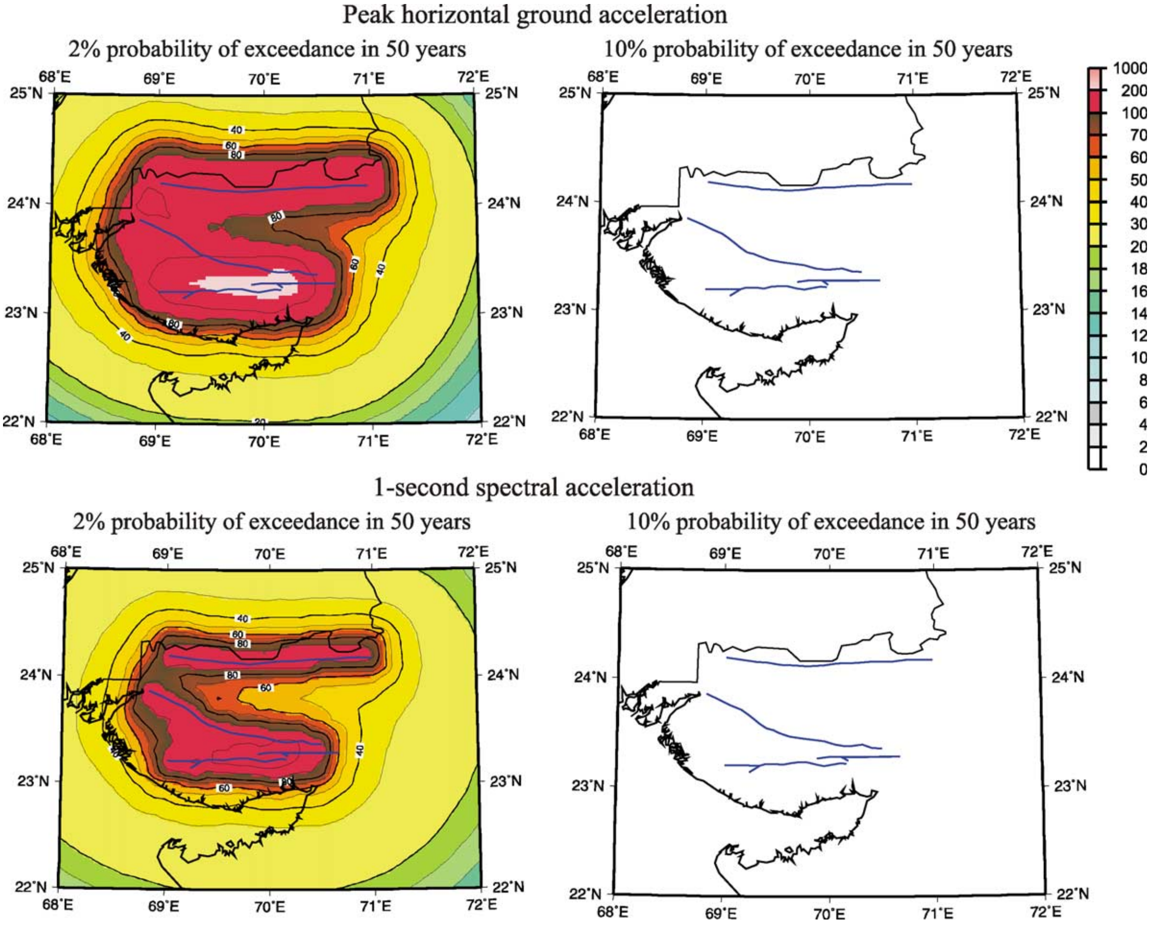

Fig. 5. Seismic hazard maps for western Gujarat for 2% and 10% probability of exceedance in 50 years based on model 3.

fault. The hazard at 10% in 50 years for model 3 is insignificant. This low hazard results from the low recurrence rates of the three faults. The three earthquakes considered in the model each have a 1600-year recurrence and, combined, only give a recurrence of about 533 years. This return period is greater than the 500-year return period for which these maps are constructed, so they do not influence the maps at this hazard level.

6. Deaggregated hazard

Seismic hazard deaggregation identifies the sources that contribute most significantly to the hazard at a given site. Whether the ground motion is caused by a more distant, larger magnitude source rather than a smaller, closer-in source can be useful information to the structural engineer, whose job it is to design structures that will resist earthquake ground shaking. In this sensitivity study, we only calculated the hazard resulting from earthquakes onn three faults. The deaggregation results are summarized as modal event magnitude, distance between the earthquake rupture

Table 2
Model 1: site, Bhuj (69.7°E, 23.2°N)

PE at 50 years (%)	Period	Motion (g)	$\hat{M}$	$\hat{R}$ (km)	$\hat{\varepsilon}$
10	PGA	0.28	7.7	10.8	−2.08
10	1-s SA	0.16	7.7	10.6	−2.26
2	PGA	1.96	7.7	8.9	0.5
2	1-s SA	1.52	7.7	4.5	0.15

Dominant fault: Kachchh Mainland.

Table 3
Model 1: site, Ahmedabad (72.8°E, 23.0°N)

PE at 50 years (%)	Period	Motion (g)	$\hat{M}$	$\hat{R}$ (km)	$\hat{\varepsilon}$
10	PGA	0.026	7.8	228	−1.1
10	1-s SA	0.035	7.8	228	−1.1
2	PGA	0.13	7.8	228	0.68
2	1-s SA	0.17	7.8	228	0.82

Dominant fault: Allah Bund.

and the site, and epsilon—the likelihood of exceeding various ground motions in terms of the ground motion probability density function. The modal source ($\hat{R}$, $\hat{M}$, $\hat{\varepsilon}$) is the single most likely source to contribute to the hazard.

The modal events are reported in Tables 2 and 3 for PGA and for 1.0-s spectral acceleration at sites in Bhuj and Ahmedabad. These deaggregations are based on the first of the 800-year recurrence models. The modal event for the second and third models is quite similar.

Examination of Table 2 for a rock site in Bhuj indicates that M 7.7 earthquakes dominate the hazard for PGA and 1-s spectral accelerations, and for both considered return periods. $\hat{\varepsilon}$ measures how many standard deviations the probabilistic ground motion is above (if positive) or below (if negative) the median ground motion. One should design important structures with some understanding of the protection relative to median motion from dominant sources, which $\hat{\varepsilon}$ helps to provide. A discussion of $\hat{\varepsilon}$ in the United States may be found in Harmsen (2001).

Examination of Table 3 shows that at Ahmedabad, the modal sources are M 7.8. This implies that the hazard is primarily contributed from earthquakes on the Allah Bund fault and, to a lesser extent, the Kachchh Mainland fault (M 7.7).

7. Results: deterministic hazard model

The deterministic hazard model gives an indication of our best estimate of the historical ground motions during the past two centuries. We apply the historical magnitudes of 7.8 for the Allah Bund, 7.7 for the Kachchh Mainland, and 6.1 for the Katrol Hill faults. For this analysis, we apply intraplate prediction equations. However, this model only accounts for median ground motions and does not take the uncertainty in the ground motion relations into consideration. In order to calculate the deterministic ground motions, we assume that each site will experience ground motions from earthquakes on each of the faults. We select the maximum of these ground motions and plot this value in Fig. 6. The deterministic median ground motion map is similar to the 2% in 50 years hazard maps for PGA.

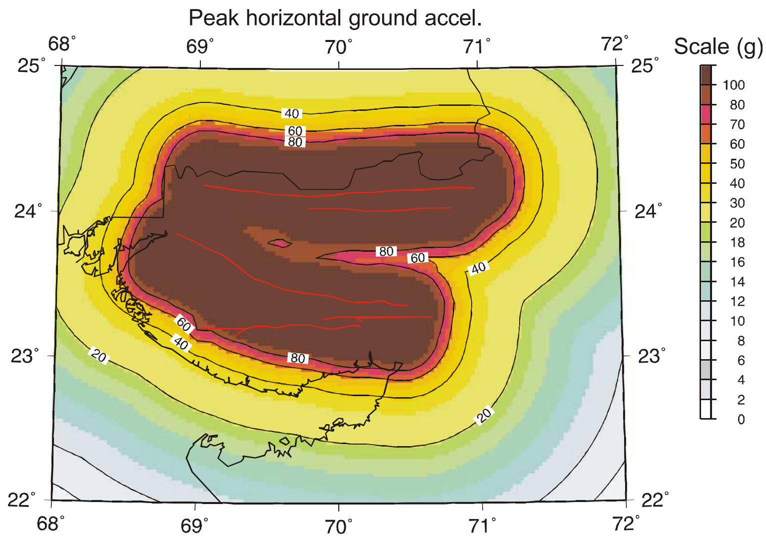

Fig. 6. Deterministic map of ground motions from earthquakes shown in Table 1.

8. Discussion and conclusions

We have conducted a preliminary seismic hazard sensitivity evaluation for the Kachchh region of northwestern Gujarat, India. The hazard was calculated for PGA and spectral acceleration with 5% damping on soft rock site conditions with 2% and 10% probability of exceedance in 50 years. The resulting ground motions for the 800-year recurrence models are significantly higher than those calculated as part of the GSHAP program even though both models have similar recurrence rates of large earthquakes. The Bhatia et al. (1999) model considers a rate of 0.126 for M $\geq$5 and a *b* value of 0.55. This model gives a rate of 0.0041 (243-year recurrence) for M $\geq$7.7 earthquakes in the zone that encompasses Gujarat. This rate is similar to our 800-year recurrence models with model 1 having a recurrence of about 400 years and model 2 having a recurrence of about 267 years for M $\geq$7.7. Using this source rate, the Bhatia et al. (1999) model obtains peak ground motions at a hazard level of 10% probability of exceedance in 50 years on the order of 0.25 *g*. However, our model results in ground motions on the order of 0.2–0.4 *g* for model 1 and 0.3–0.7 *g* for model 2. The primary difference between the Bhatia et al. model and our model is that we applied intraplate attenuation relations for this region.

We emphasize that our seismic hazard evaluation for the Kachchh region is only preliminary because: (1) we have not included sources to account for random earthquakes on unknown faults; (2) we have not developed a preferred seismotectonic model with reasonable uncertainties; (3) we have not completed a thorough examination of the attenuation relations for India; (4) we have assumed recurrence rates that were highly conjectural; and (5) we have not incorporated site effects. However, this hazard analysis suggests that large PGAs (greater than 0.8 *g*) have occurred in the historic record and that large ground accelerations will occur as a result of future large earthquakes in Gujarat.

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